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SECOND HARMONIC ZONE INJECTION FOR AMPLIFIER LINEARISATION

Tayfun Nesimoglu, Ross J. Wilkinson, C. N. Canagarajah, J. P. McGeehan

Center for Communications Research,
University of Bristol,
University Walk, Bristol BS8 1TR, United Kingdom
e-mail: T.Nesimoglu@Bristol.ac.uk, Tel: 0117 928 7740

Abstract - Second Harmonic Zone (SHZ) Injection is a feedback technique for reducing the intermodulation distortion (IMD) at the output of an amplifier, which is based on feeding the SHZ intermodulation products (IMP), back to the amplifier's input. The technique is analyzed theoretically and practical results demonstrate the linearisation performance. Two feedback prototypes were built, one using a frequency doubler and the other using a buffer amplifier as a distorter, where 14 dB and 13 dB improvement was obtained respectively in reducing the third order IMP (IMP_3). The performance of the technique with changing frequency and input power level was also investigated.

I. INTRODUCTION

THE spectral efficiency of mobile and wireless communication systems has become an important issue due to the increasing number of users and services [1]. This motivated the research into designing linear transmitters to increase the spectral efficiency by reducing the distortion level. The main source of nonlinearity in a communication channel is the RF power amplifier (PA). The nonlinear PA distorts the input signals and generates additional signals at the output, known as IMP. This spreads the spectrum over a wider bandwidth creating adjacent channel interference (ACI), crosstalk, and distortion, which reduces the signal-to-noise ratio (SNR). Therefore, channel spacing in a multichannel system has to be increased, reducing the spectral efficiency by allowing fewer channels in the available bandwidth.

Available linearisation techniques use complex circuits, and are expensive to produce. These factors limit the size and make them unsuitable for mobile equipments. The Feedforward technique [2] requires another amplifier, reducing the overall efficiency of the system. Also the sensitivity to the matching of the two loops in the system,

resulted an extensive research for an adaptive feedforward system [3]. Cartesian Feedback [4] requires a complicated feedback path, therefore its linearisation bandwidth is limited. The Predistortion circuits [5] are very sensitive to input power changes, therefore digital signal processing (DSP) is applied to the predistorter for adaptivity, the result is a large and expensive amplifier circuit. Compared to other linearisation schemes, our technique requires a smaller and less complicated circuit. It can easily be combined with other linearisation techniques producing a hybrid scheme, improving the performance of the whole system. This technique has been previously investigated by computer simulation [6], which shows a considerable improvement of 50 dB. Practical experiments [7] were also made, but instead of feeding back the SHZ, one of the second harmonics was externally generated and injected into the amplifier, where a 16 dB improvement was obtained in reducing only one of the IMP_3 .

The organization of the paper is as follows. In Section II, the theory is explained and mathematical analysis is shown. Section III and Section IV present the results obtained from two feedback prototypes and also the performance with changing frequency separation and input power level.

II. THEORETICAL ANALYSIS

This technique uses the distortion energy in the SHZ to reduce the IMD generated about the wanted signals. A typical amplifier output is shown in Fig.1. Third and fifth order IMP appear very close to the fundamental tones with high power levels, which makes them impossible to be filtered out. When the input contains two signals with fundamental frequencies f_1 and f_2 , the nonlinear PA cause the signals to interact, and the output consists of all the IMP_3 at $(nf_1 \pm mf_2)$ where $n, m = 1, 2, 3, \dots$. If the SHZ signals at $2f_1$, $f_1 + f_2$ and $2f_2$ are injected into the amplifier

together with the fundamental signals, the nonlinear PA will create additional IMP_3 at the frequencies $2f_1-f_2$ and $2f_2-f_1$. By changing the amplitude and phase of the injected signals, these additional IMP_3 and the original IMP_3 can be made equal in amplitude and out of phase. The result will be the elimination of the IMP_3 . Mathematical analysis can be made by using the first three terms of a Taylor expansion [8]

$$V_o = a_1 V_{in} + a_2 V_{in}^2 + a_3 V_{in}^3 \quad (1)$$

where the input of the amplifier is V_{in} , nonlinear parameter is a_n ($n=1, 2, 3$) and the output is V_o . When the input of the amplifier is two signals at frequencies f_1 and f_2 with common power level A , one of the IMP_3 at frequency $2f_1-f_2$ can be written as:

$$IMP_3 = \frac{3}{4} A^3 a_3 \cos(2\omega_1 t - \omega_2 t) \quad (2)$$

The SHZ signals will be fed back to the amplifier's input and combined with the two fundamental signals. Then the input of the amplifier can be written as :

$$V_{in} = A (\cos \omega_1 t + \cos \omega_2 t) + B (\cos(2\omega_1 t + \phi_1) + \cos(2\omega_2 t + \phi_2)) + C \cos(\omega_1 t + \omega_2 t + \phi_3) \quad (3)$$

Where B and C are the amplitudes of the second harmonics, and the second order IMP respectively. Since the SHZ will be taken from the output, their phases (ϕ_1 , ϕ_2 and ϕ_3) cannot be adjusted individually, so it can be assumed that all the injected signals will have a common phase ϕ . The amplitude adjustment will also be common, so the ratio between second harmonics and second order IMP will be constant in the feedback path. This ratio r can be written as $C=Br$. After these assumptions, IMP_3 in terms of B at $2f_1-f_2$ is:

$$\begin{aligned} IMP_3 = & \frac{3}{4} A^3 a_3 \cos(2\omega_1 t - \omega_2 t) + \\ & A a_2 B \cos(2\omega_1 t - \omega_2 t + \phi) + \frac{3}{2} A a_3 B^2 \cos(2\omega_1 t - \omega_2 t) \\ & + 3 A a_3 B^2 r \cos(2\omega_1 t - \omega_2 t) \end{aligned} \quad (4)$$

The first term is the IMP_3 produced by the fundamental signals and is equal to (2). The other terms are the extra IMP_3 produced by the injected signals. The complete cancellation of IMP_3 will be achieved when (4) reaches zero. This can be achieved by amplitude and phase adjustment of the injected signals. In this case, the most suitable phase required is 180° , and the amplitude of the second harmonic B should satisfy the condition:

$$B = \frac{2a_2 + \sqrt{4a_2^2 - 18A^2 a_3^2 (1+2r)}}{6a_3 (1+2r)} \quad (5)$$

It can also be seen that, as the ratio r gets larger, same cancellation of IMP_3 can be achieved by lower second harmonic power levels, which means that the second order IMP appearing at the frequency f_1+f_2 is more dominant in reducing the IMP_3 .

III. FEEDBACK WITH FREQUENCY DOUBLER

The feedback prototype was built as shown in Fig.2. The output of the power amplifier P_{out} is sampled by a directional coupler. Since the sampled power is not at the required level to linearise the PA, a buffer amplifier is needed on the feedback path. After buffer amplifying, a high level of fundamental zone still exists in the spectrum. Instead of filtering out and wasting this power, a frequency doubler is used to generate more SHZ products. By this method their power level is increased considerably without needing further amplification. The high-pass filter (HPF) is operating at the SHZ. After filtering, phase and amplitude adjustment was made with voltage-controlled phase shifter and attenuator. The output of the feedback path P_{inj} is then combined with the input signals P_{in} and injected into the amplifier.

The amplifier used in the experiment is a Class A amplifier with 30 dB gain. The input of the amplifier is two tones at frequencies 430 MHz and 450 MHz with -23 dBm common power level, which is the 1 dB compression point of the PA. The output spectrum is shown in Fig.1, which is sampled by a 20 dB directional coupler and amplified by 11 dB. The frequency doubler further increases the power level in the SHZ by 18 dB. The HPF operates at 800 MHz (SHZ). The voltage-controlled attenuator and the phase shifter are adjusted to obtain the minimum value of IMP_3 , as shown in Fig.3, where an improvement of 20 dB is obtained. The linearisation scheme does not reduce the gain of the PA. By comparing Fig.1 and Fig.3, it can be seen that the fifth-order IMPs are increased by 1.5 dB. A compromise point can be found where the third and fifth-order IMPs are at the same level, by another amplitude and phase adjustment. The output spectrum at this point is shown in Fig.4, with an improvement of 14 dB.

The performance of this feedback circuit was investigated with changing frequency separation (Δf) and power level of the fundamental signals. Fig.5 shows the IMD response with changing Δf . Each one of the plots

represents one of the IMP_3 . The initial Δf is 20 MHz and initial reduction is 13 dB. Increasing or decreasing the Δf changes the level of the IMP_3 asymmetrically. The zero point represents the point where there is no reduction in the distortion level. Linearisation bandwidth is important for all the linearisation schemes. Broadband modulation schemes require wide linearisation bandwidths, therefore our technique's linearisation bandwidth needs to be improved considerably.

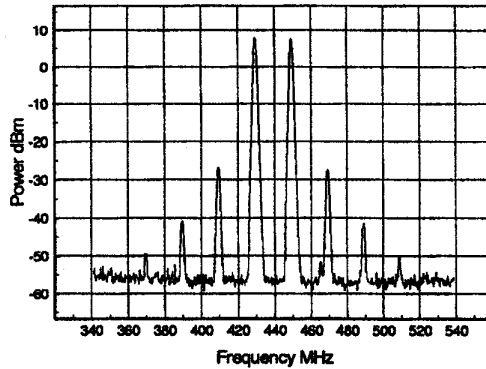


Fig. 1 Two-tone test on class A amplifier.

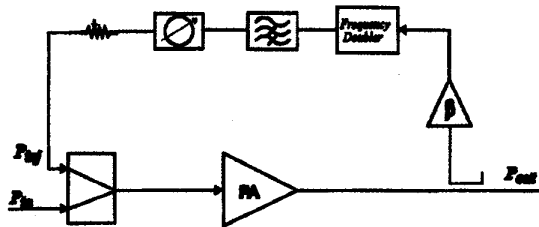


Fig. 2 Harmonic feedback with frequency doubler.

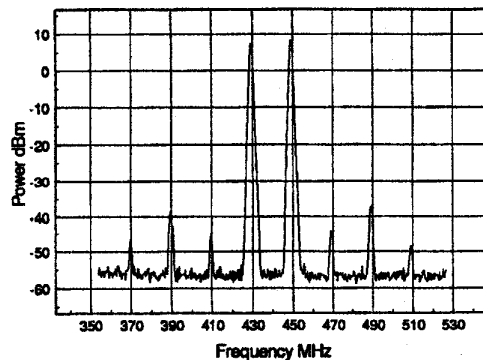


Fig. 3 Maximum improvement of IMP_3 .

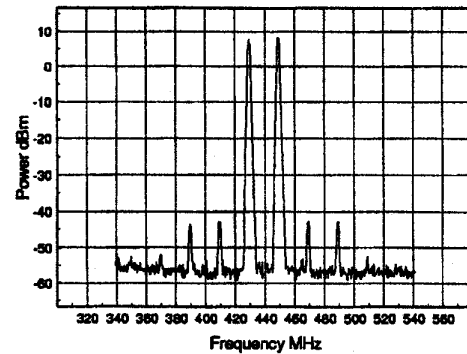


Fig. 4 Equal improvement on third and fifth IMP .

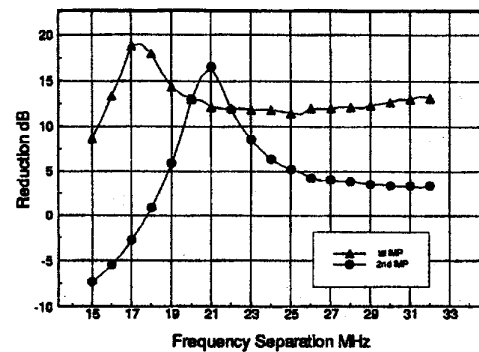


Fig. 5 Performance with changing Δf .

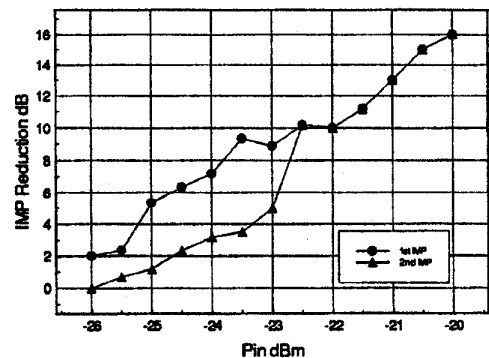


Fig. 6 Performance with changing power level.

Performance with changing power level is investigated by reducing the input power level from -20 dBm to -26 dBm. The linearisation response obtained is shown in Fig.6. The initial reduction is 16 dB at -20 dBm input power level.

IV. FEEDBACK CIRCUIT WITH DISTORTER.

The prototype built for this circuit is exactly the same as the previous one, except this one does not contain a frequency doubler. The buffer amplifier on the feedback path is used as a distorter rather than an amplifier. It has a lower bias point and increases the SHZ by 21 dB while amplifying the fundamental tones by only 2.33 dB. The input of the buffer amplifier is shown in Fig.7, and the output in Fig.8. The uncompensated output of the amplifier is shown in Fig.9. After connecting the feedback path to the input and adjusting the amplitude and phase, 13 dB improvement is obtained with equal level third and fifth IMP, as shown in Fig.10.

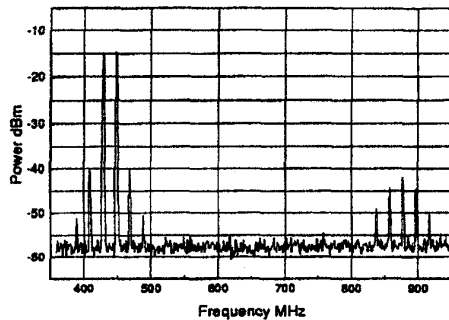


Fig. 7 Input of the buffer amplifier.

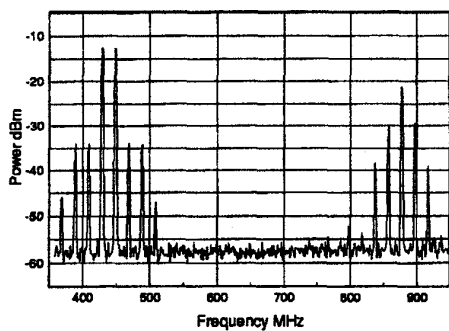


Fig. 8 Output of the buffer amplifier.

The performance of the linearisation scheme with changing Δf and input power was investigated. The initial Δf between the tones is 20 MHz, and the reduction obtained at this point is 13 dB. Reducing and increasing the Δf degrades the linearisation performance, but it is behaving more symmetrically than the previous circuit

with the frequency doubler in the feedback path. The frequency response of this circuit is shown in Fig. 11.

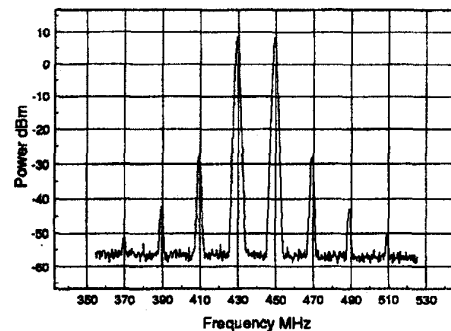


Fig. 9 Two tone test on class A amplifier.

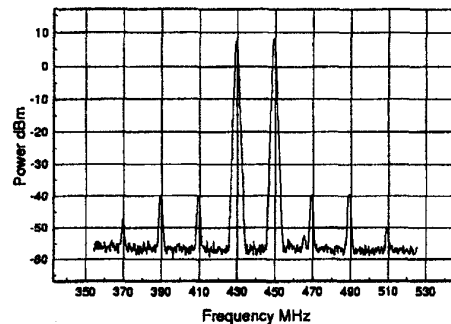


Fig. 10 Equal improvement on third and fifth IMP.

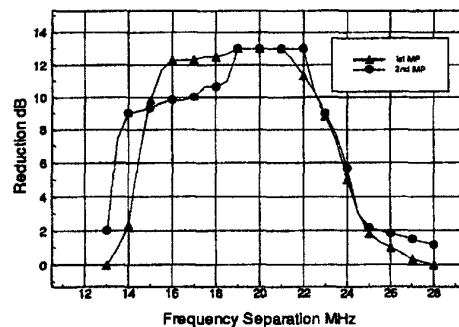


Fig.11 Performance with changing Δf .

The input power level was changed from -20 dBm to -26 dBm. Initial reduction is 13 dB at -20 dBm input power level, the plot representing this response is shown in Fig.12. Again the IMP are behaving more symmetrically than the previous case.

Any nonlinearity in the feedback path directly reflects on the output of the amplifier. Since the amplitude and the phase adjustments of the SHZ are critical to the performance of the linearisation scheme, any source of amplitude and phase nonlinearity should be avoided. The frequency doubler is a nonlinear element which behaves differently at different frequencies and amplitudes, thus removing the frequency doubler from the feedback loop has made the lineariser less susceptible to changing frequency and input power.

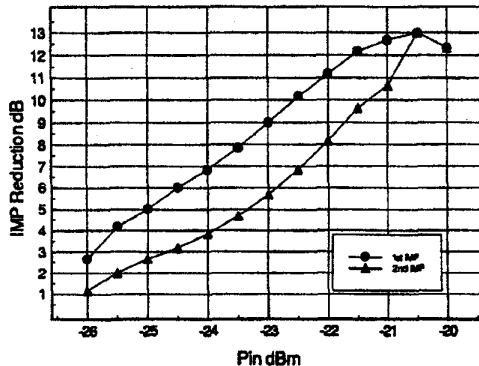


Fig. 12 Performance with changing input power level.

V. CONCLUSIONS

In this paper, the Second Harmonic Zone Injection technique has been presented using theoretical analysis and practical results. The results obtained from the two prototypes show that IMD can be reduced by feeding back the SHZ signals with suitable amplitude and phase. Up to 14 dB improvement is obtained at 450 MHz, with a simple and low-cost circuitry. The tests carried out with changing input frequency and power level show the importance of the amplitude and phase linearity of the feedback path, which will be the focus of future research to achieve a wider linearisation bandwidth.

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